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Status and results from the S-POD collaboration

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STFC/ASTeC/RAL
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Outline

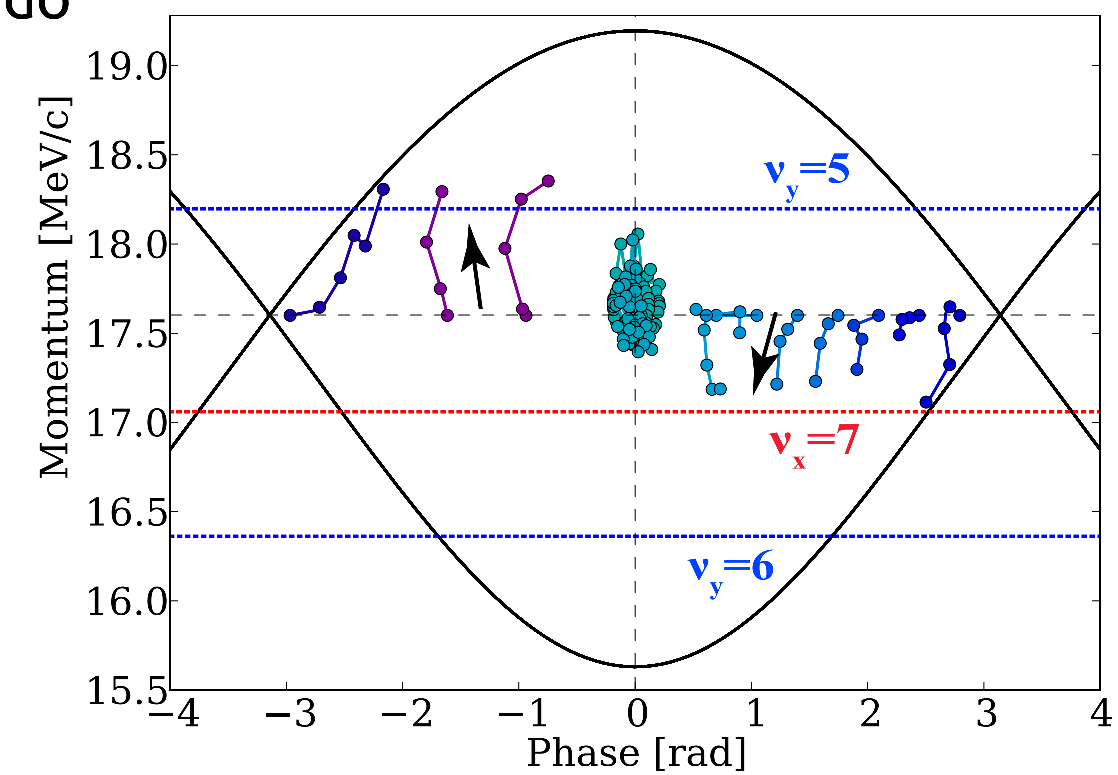
- Motivation
- The S-POD experiment - what is it?
- Our collaboration so far
- Experimental resonance crossing studies
  - Single resonance crossing
  - Multiple resonance crossing
  - Nonlinear effects
- Topics for future study
- Plans at RAL

Motivation (1)

Resonance crossing, particularly of integers is a *key concern* in the FFAG community, particularly with the development of non-scaling FFAGs.

In EMMA and other accelerators, it can be difficult to do slow resonance crossing studies due to:

- Limited parameter range (RF)
- Coupling to longitudinal plane
- Lack of range of control for driving terms
- Time consuming experiments



Slow resonance crossing in EMMA, all particles lost for tune crossing rate 0.01 to 0.1/turn (ring tune)

Image source: J. Garland.

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Motivation (2)

There are many questions to address, particularly for FFAGs:

- How do nonlinear effects come into play?
- Can we mitigate resonance crossing effects in FFAGs?
- Does space charge make a difference?

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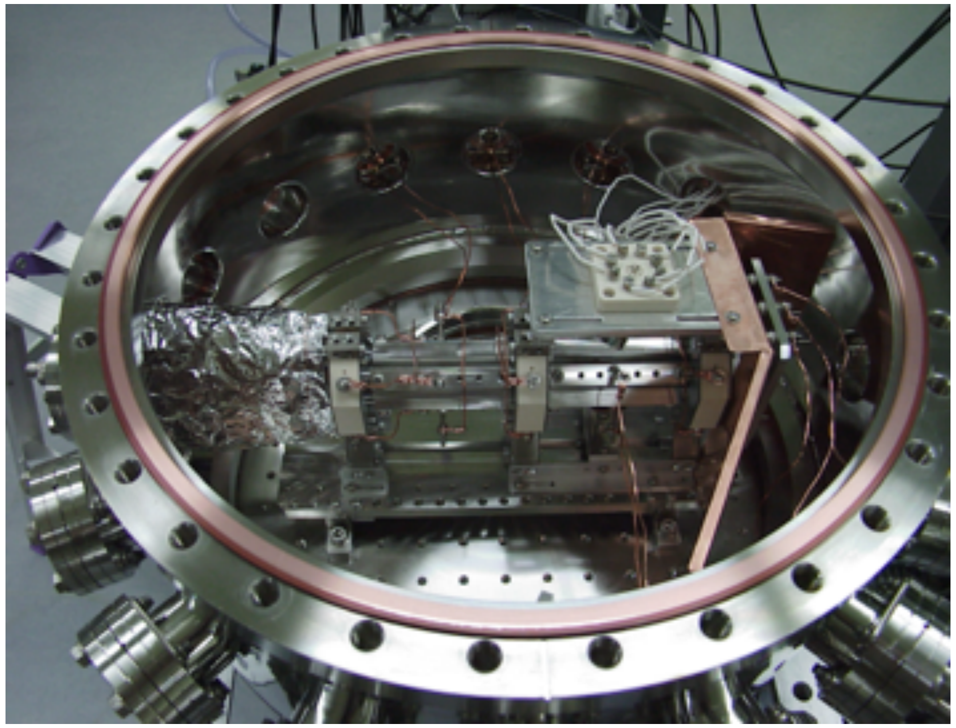
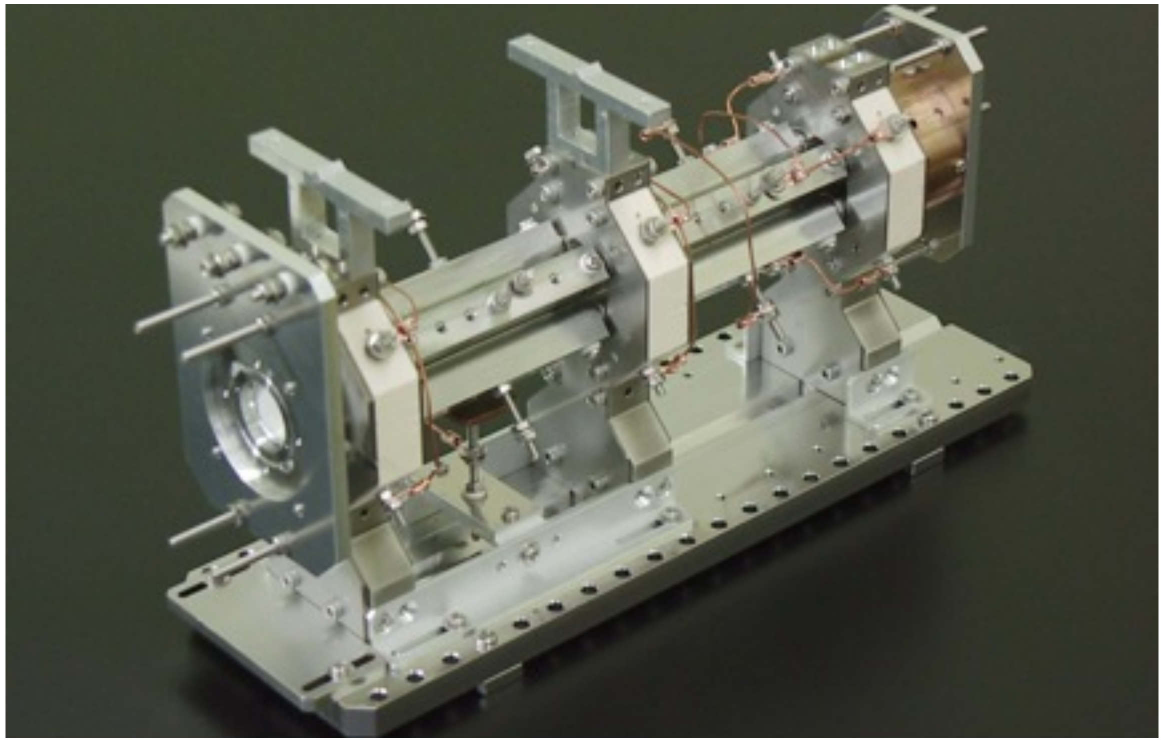
S-POD: Simulator of Particle Orbit Dynamics
at Hiroshima University

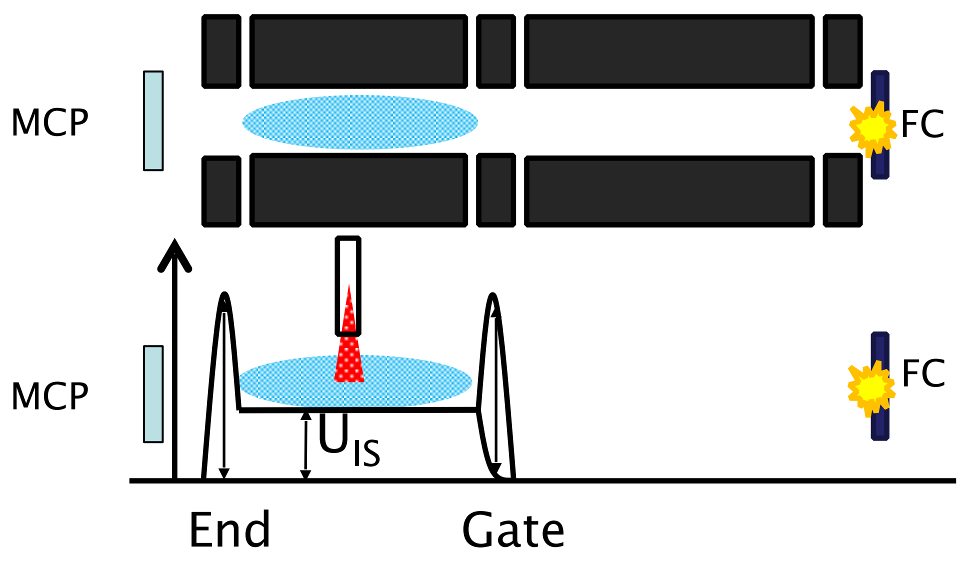
S-POD is a tabletop sized linear Paul trap device which can simulate a focusing channel in an accelerator (including space charge)

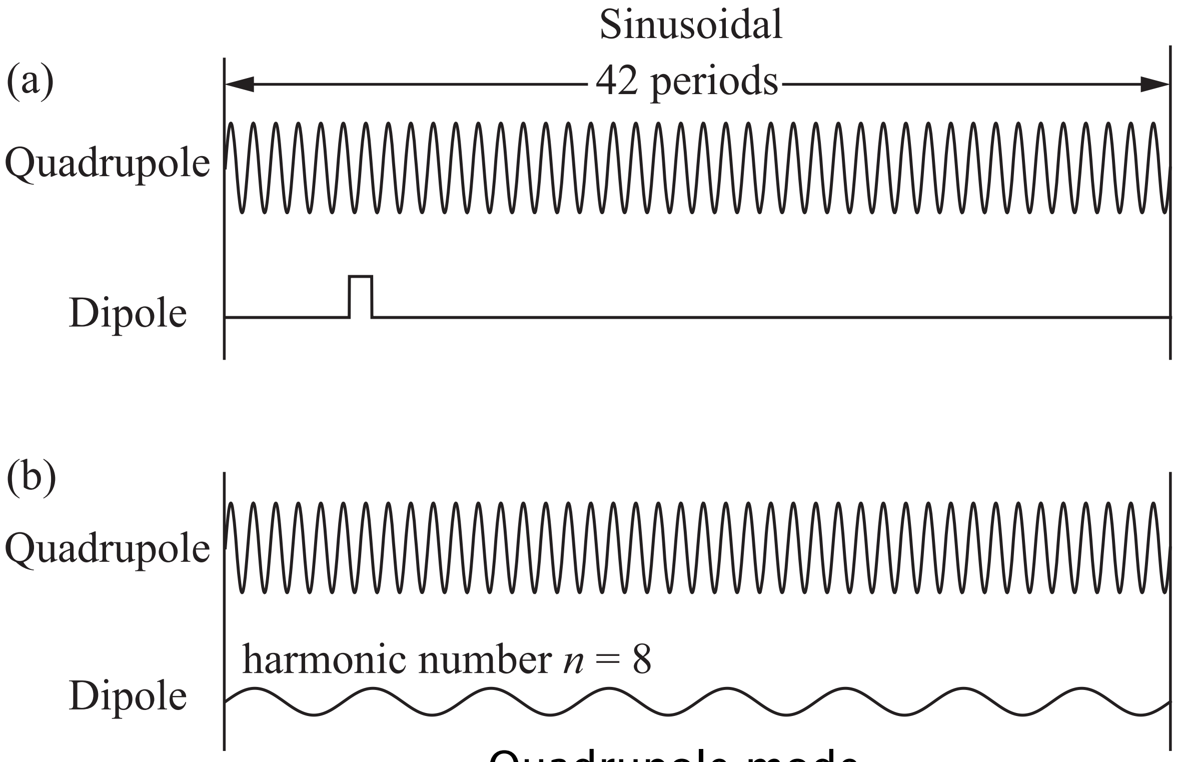




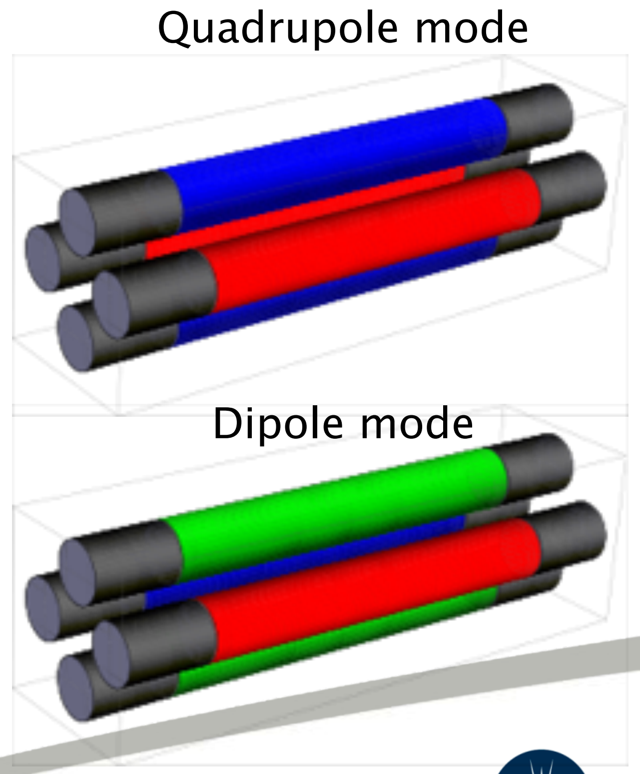
How does S-POD work?

Linear Paul traps are 'standard' devices for confinement of non-neutral plasmas





- Ar+ gas ionised by e- gun
- Trapped longitudinally in a potential well
- 1 MHz confinement wave applied to quadrupole rods
- Add a perturbation wave



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Why is S-POD suitable for our studies?

- Hamiltonians in the two systems have correspondence

$$H_{\mathrm{beam}} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2}K(s)(x^2 - y^2) + \frac{q}{p_0\beta_0 c\gamma_0^2}\phi$$

Hamiltonian for transverse beam motion

$$H_{\mathrm{S\text{-}POD}} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2}K_{\mathrm{p}}(\tau)(x^2 - y^2) + \frac{q}{mc^2}\phi_{\mathrm{sc}}$$

Hamiltonian for Paul trap

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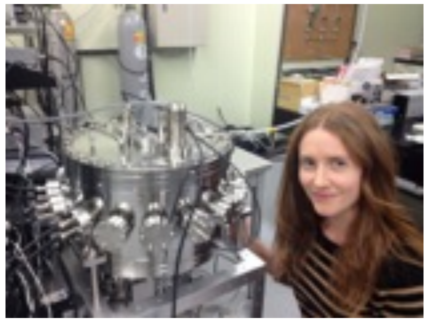
S-POD Collaboration so far

- ASTeC IB Group & Hiroshima University Beam Physics Group
- First visit from RAL group in late 2012 (after FFAG workshop)
- Regular Skype meetings
- Short experimental visit in Nov'13
- MoU signed after visit in March '14



Preliminary results shown in IPAC'13 and IPAC'14 papers

First peer reviewed paper submitted to PRSTAB

An experimental study of integer resonance crossing in a non scaling fixed field alternating gradient accelerator with a Paul ion trap

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Abstract

An experimental study is presented of the phenomenon of integer resonance crossing pertaining to non-scaling fixed field alternating gradient accelerators. A compact ion trap known as a Paul trap is applied to this problem in order to study integer resonance crossing phenomena over a wide parameter range. Employing the S-POD trap system at Hiroshima University in a setup that mimics the EMMA non-scaling FFAG, we have verified the theoretical prediction of the coherent excitation of dipole motion over a wide range of error and crossing speed. In addition, the cancellation of amplitude growth depending on relative betatron oscillation phase between two consecutive resonances is observed and studied. We also explore nonlinear effects and in particular the effects of amplitude dependent tune shifts and find that these nonlinear effects are a key factor in understanding our experimental results.

Prof. Hiromi Okamoto's group in Hiroshima

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Method of S-POD Experiments

In many cases, it is faster to carry out the S-POD experiment than to run the equivalent simulation

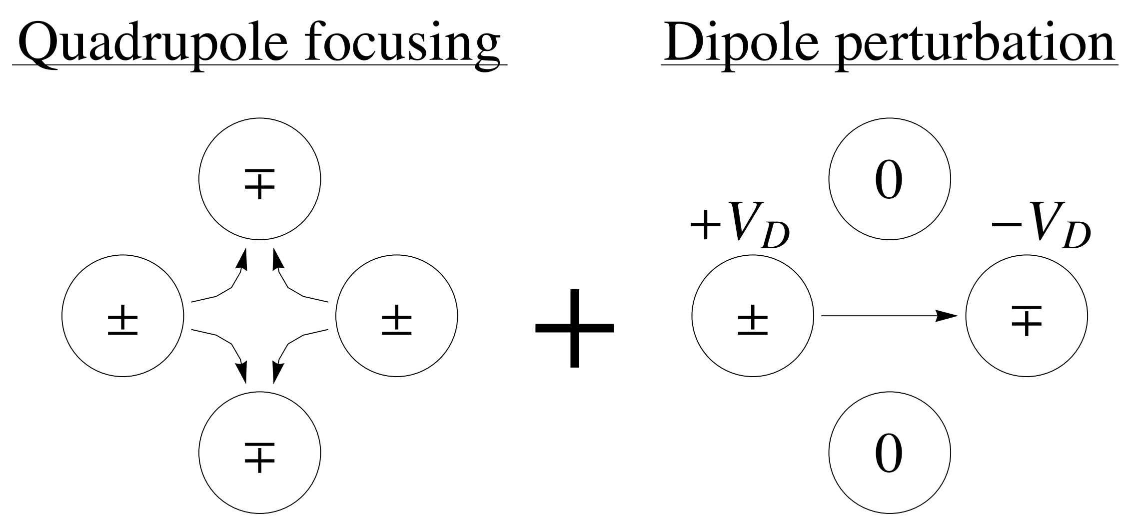
Control the tune by varying voltage of RF wave

In an accelerator focusing varies with s.
In S-POD we vary focusing with time.

We can (in principle) have any lattice structure we like - FODO, FDF, FDDF etc…

Wait some period (accumulation time), then extract remaining plasma onto MCP

Motion with dipole perturbation



$$\frac{d^2 x_{\mathrm{COD}}}{ds^2} + K_x(s) x_{\mathrm{COD}} = -\frac{\Delta B}{B\rho}$$

COD equation of motion in circular accelerator

$\longleftrightarrow$

$$\frac{d^2 x}{d\tau^2} + K_{rf}(\tau) x = -\frac{q}{mc^2 r_0} V_D(\tau)$$

Equation of motion in S-POD with dipole perturbation field

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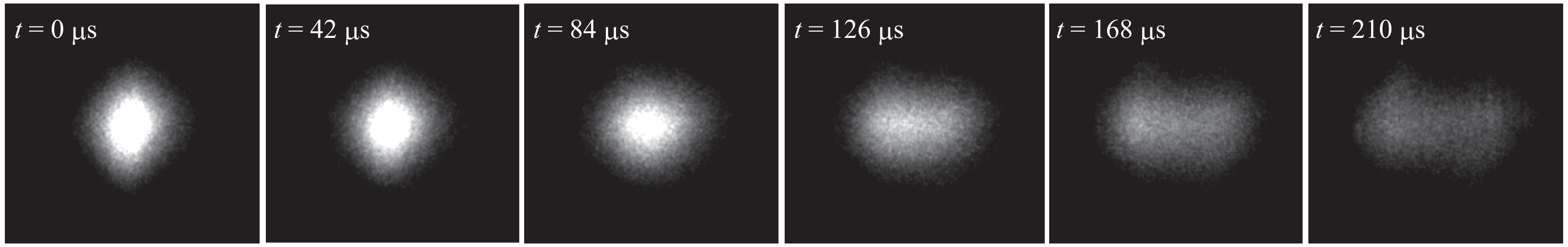
Establishing integer stopbands with dipole perturbation

- On resonance, we clearly see large ion losses
- Can also see a clear widening in the distribution

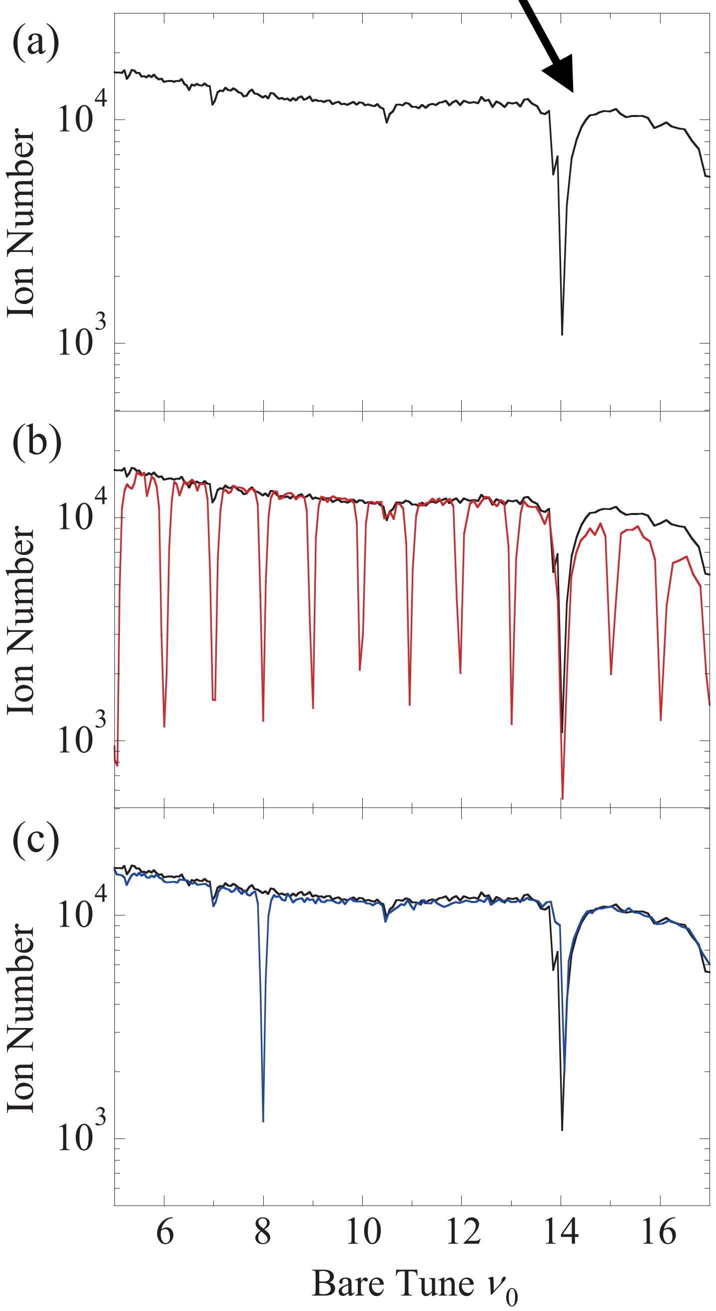


nb: each image is axially integrated distribution

Note that we can excite each integer individually by expanding dipole field into fourier harmonics:

$$\frac{\Delta B}{B\rho} = \sum_n b_n \cos(n\theta + \phi)$$

3rd order due to trap misalignment

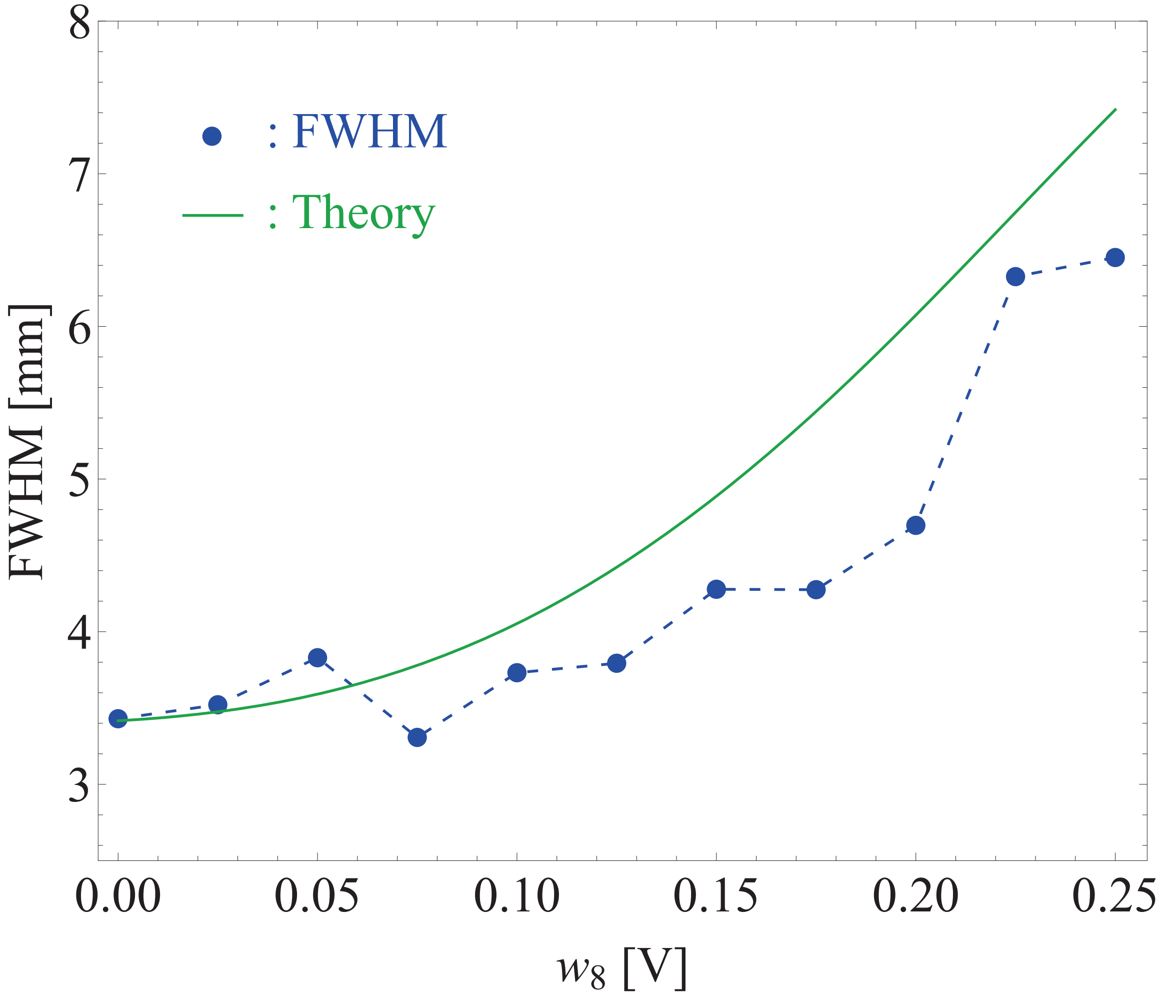


Amplitude growth with error

We wanted to confirm amplitude growth when OFF RESONANCE as well

Theory = Gaussian distribution integrated over COD trajectory

tune = 8.1, varying perturbation strength

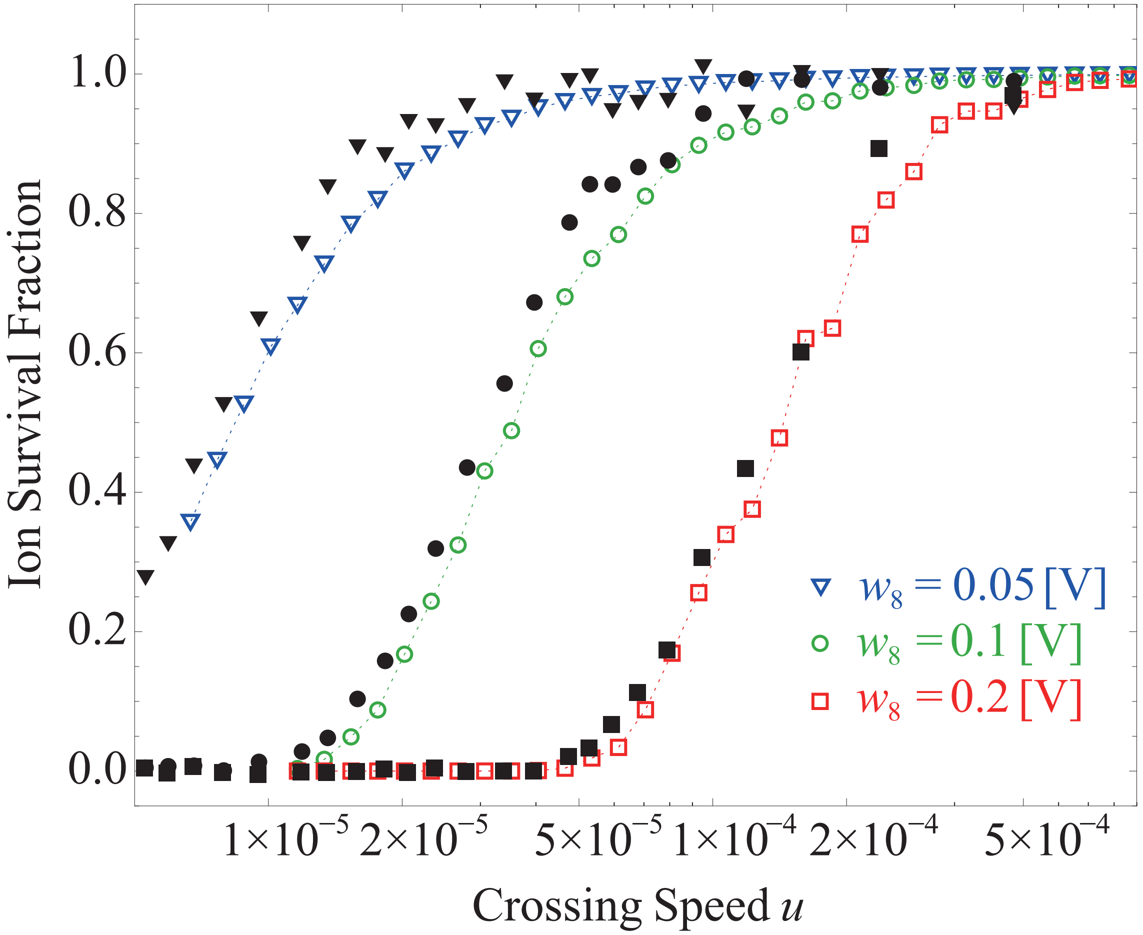


Single resonance crossing

crossing speed, $u = \dfrac{\delta \nu_{\text{cell}}}{n_{\text{rf}}}$

In EMMA, for 10 turn extraction u is roughly 5×10^{-4} if the tune per cell decreases by 0.2 during acceleration

8th harmonic excited
Tune varied 9.5 -> 7.5



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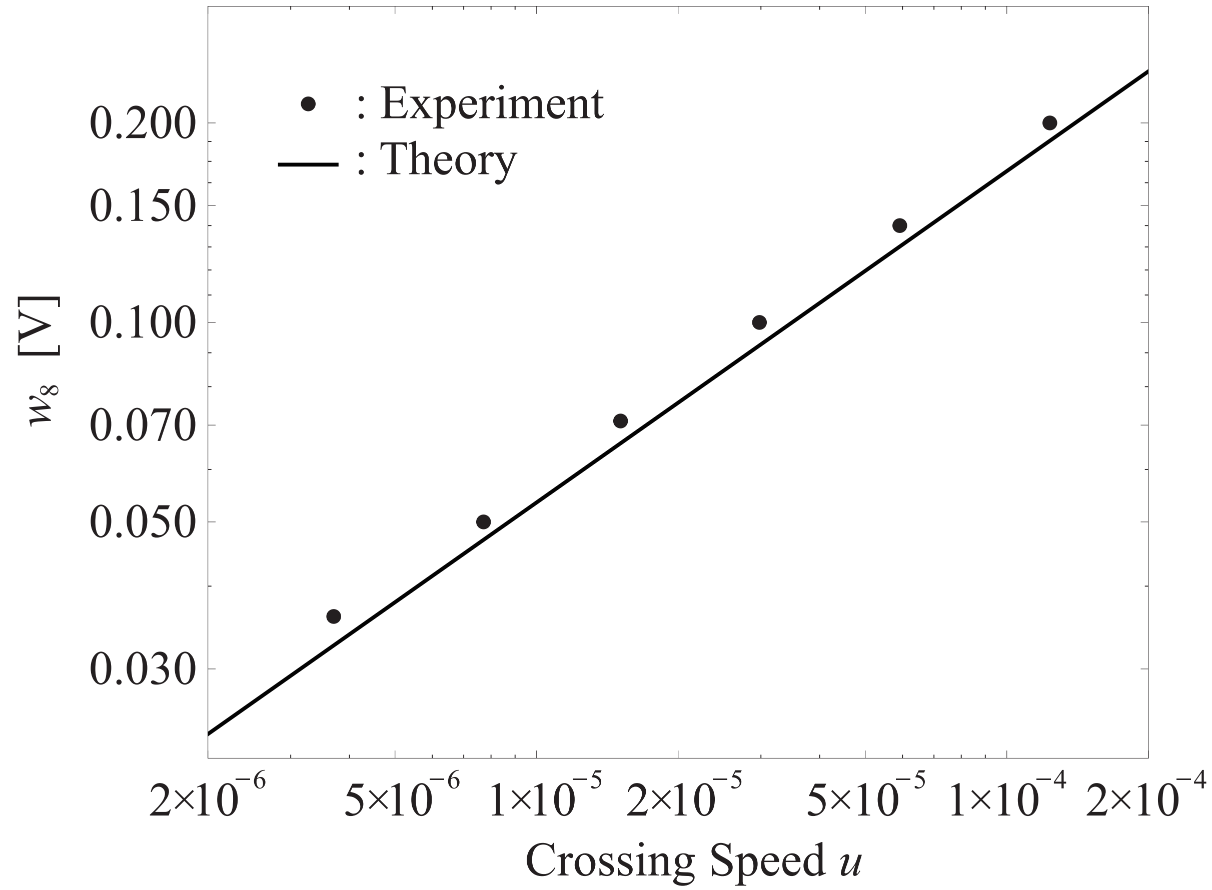
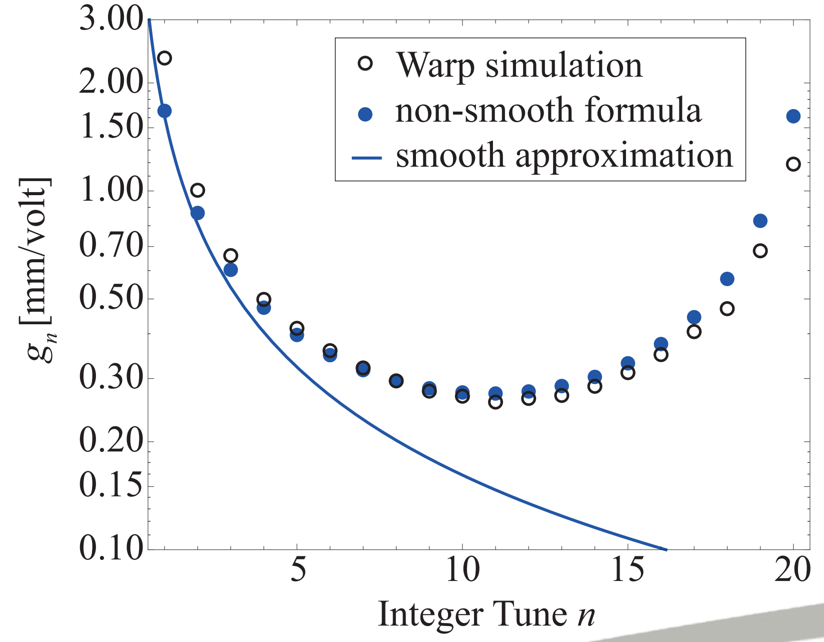
Amplitude growth vs. crossing speed



Critical perturbation voltage at which the maximum transverse shift of the plasma centroid reaches 5 mm (the LPT aperture) after single resonance crossing at $\nu_0 = 8$



nb. we use the non-smooth formula to find g coefficient for amplitude growth

$$\Delta A_n = g_n \frac{w_n}{\sqrt{u}}$$

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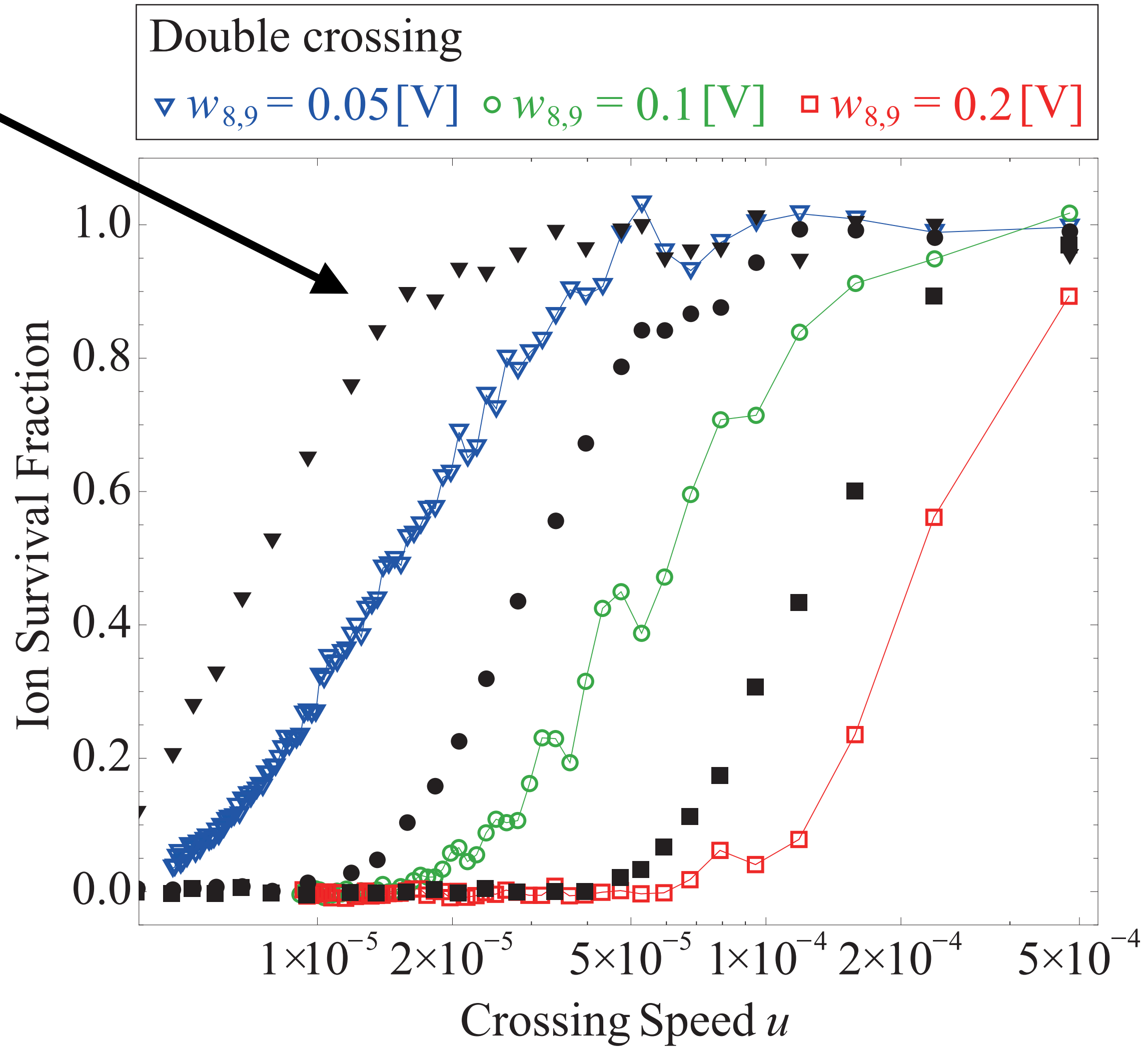
Result 3: Double resonance crossing

- Single crossing for comparison (black)
- Oscillatory behaviour for high perturbation strength… why?



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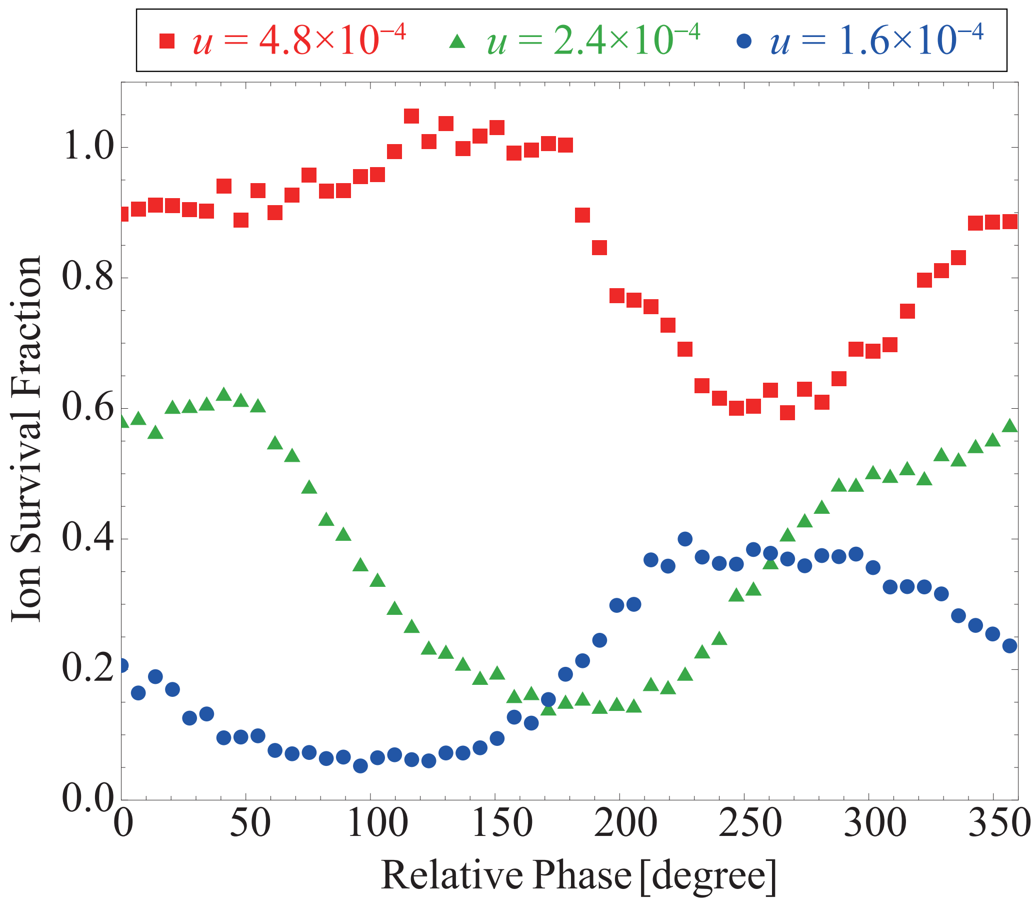
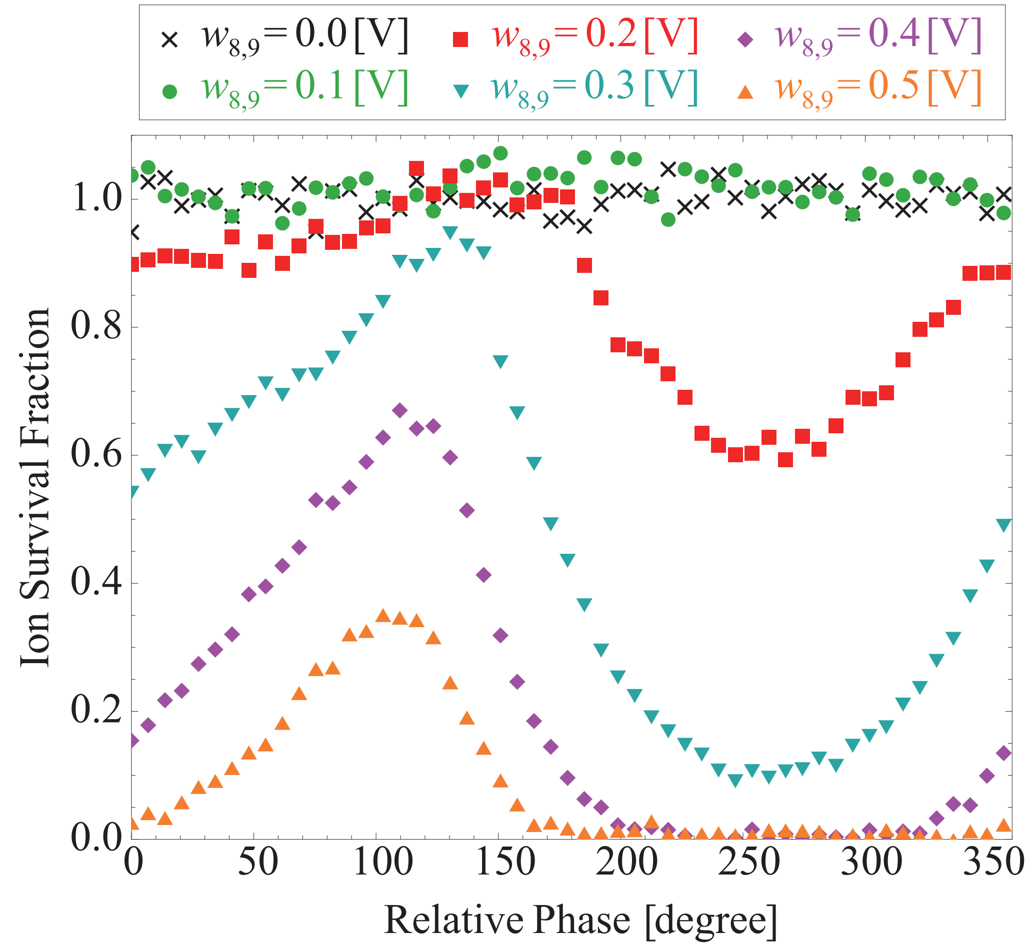
Result 4: Phase dependence effects

Vary phase of 8th harmonic, cross 9th & 8th





Fixed perturbation
Varying crossing speed

Fixed crossing speed
Varying perturbation

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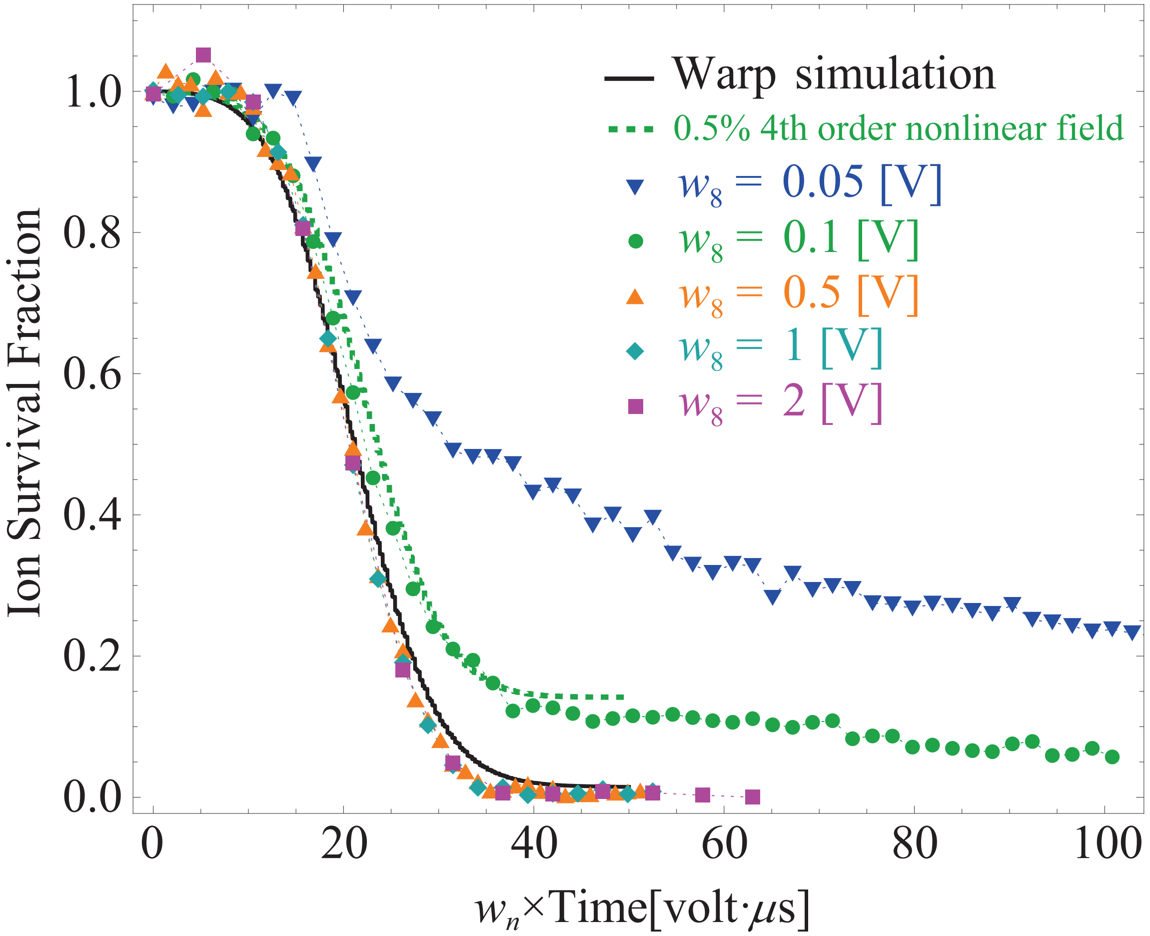
Result 5: Nonlinear effects

- If purely linear, loss would always go to zero…
- With amplitude dependent tune shift, particles shift off-resonance
- 'Plateau' effect observed and studied
- Full analysis in progress



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Future collaborative research topics

This technique has wide-ranging applications and will allow us to establish understanding in beam dynamics topics which are vital for the design of future high power proton or ion accelerators.

Completed:

- Integer resonance crossing:
  - Single & double crossing, phase-dependent effects, nonlinear effects

Current:

- Effects of coupling, detuning effects due to nonlinearities, long term effects

Future:

- Combination of the resonance crossing with intense beams is a natural extension
- Lattice variants and higher order stability regions
- Systematic study and control of non-linear effects (possible CERN PS topics)
- More general non-linear beam dynamics (with ISIS & CERN)

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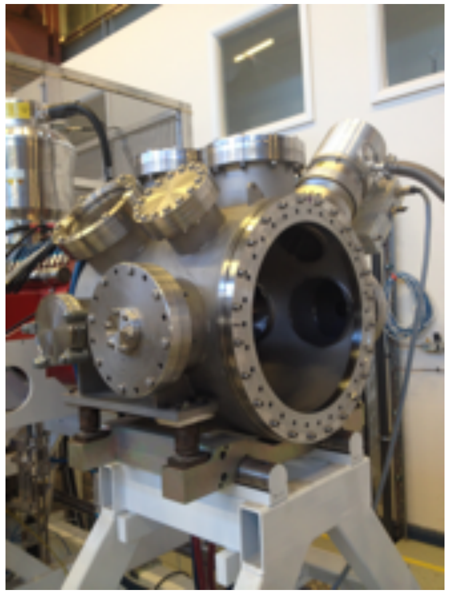
S-POD at RAL

- We plan to build an S-POD “Simulator of Particle Orbit Dynamics” ion trap apparatus at RAL.
- Funds have now been allocated by ASTeC (Sept 2014)
- The new trap apparatus will be complementary to the existing setup at Hiroshima and built in close collaboration.
- We hope to control non-linear components in order to study non-linear phenomena and space charge effects.
- This will allow the two groups to build on their existing collaboration and to expand the range of topics covered.



Possible vacuum chamber to re-use

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Summary

- Integer resonance crossing studied in detail, and including non-linear effects is important to understand the results
- Potential to look at many topics of interest to FFAGs & other machines as a complementary tool to real accelerators
- We hope to build a new trap system in the UK

We welcome your feedback, input and ideas as always!

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